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The impact of climate change on grapevine phenology and the influence of altitude: A regional study

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ABSTRACT

Simulations of the effect of climate change on the phenology of grapevines indicate shorter growing seasons, earlier occurrences of phases and shorter phase duration in the future. The impact varies depending on the geo-localization of the studied region and its microclimate. The objective of this study is to further understand the impact of climate change on grapevine phenology by studying the role of varieties and microclimates through a regional assessment carried out in two future periods of time (2021–2050 and 2071–2099). The influence of altitude on phenological stages was studied on five different phenophases for five grapevine varieties in the province of Trento (Italian Alps). The model predicts a significant advance for all phenological stages (advanced harvest up to four weeks), which could affect the quality and suitability of the region for the selected varieties. In particular, the model indicates shorter phenophases and a shorter time between bud break and harvest, from one to three weeks. Furthermore, projected phenological changes are not homogeneous in the region under study: more pronounced effects of the temperature increase are expected at higher altitudes. Indeed, phenological advance is more pronounced for varieties grown at higher altitudes. On the contrary, phase duration and growing season length are more affected on the varieties grown at lower altitudes. A lower spread of harvest timing is expected in altitudinal transects, up to 3 days for every 100 m. We can conclude that adaptation strategies such as change of varieties, harvest management and wine making technologies will be necessary to cope with the effect of climate change.

1. Introduction

During human domestication and exploitation of *Vitis vinifera*, the story of grapevine spread across Europe has been deeply interlaced with that of climate evolution (Chevet and Soyer, 2006; Mariani et al., 2009). In the near future, climate change is expected to significantly influence grape and wine quality (Jones et al., 2005a). In fact, temperature is the main driver of grapevine phenology (Gladstones, 2011; Bock et al., 2011). Several studies have assessed, both at global and regional scales, the influence of temperature increase in the last century (Jones and Davis, 2000; Jones et al., 2005a; Dalla Marta et al., 2010) and predicted future trends (Webb et al., 2007; Bock et al., 2011). In a regional study, the Winkler and Huglin Indices (Amerine and Winkler, 1944; Huglin, 1978) were used to compile daily phenological data for a time span of 45 years (1964–2009), with a reported increase in temperature and the associated shift of phenological events (Tomasi et al., 2011). The same trend is also confirmed by Jones et al. (2005b) in a continental study in nine European wine-growing areas in five countries. Correlation between grapevine phenology and climate variables varied depending on phenophases: maximum temperatures highly influenced early season events (bud break and bloom), while average temperatures, growing degree-days (Winkler index) and Huglin index values were more important for later season events (veraison and harvest). Webb et al. (2007) studied six wine-growing regions covering the main part of Australian viticultural area, using the VineLogic model (Godwin et al., 2002) in a simulation for the years 2030 and 2050. The impact of climate change varied depending on the region, with highest differences for the first phenophase (budburst). These studies show that the temperature rise is highly correlated to the earlier occurrence of phenological phases, which may also affect the final quality of products (Jones and Davis, 2000; Jones et al., 2005a; Dalla Marta et al., 2010; Bock et al., 2011). Earlier phenological events have been already

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reported for the European wine zones in Italy, France and Germany (Chuine et al., 2004; Bock et al., 2011). Temperature increase has been considered responsible for an advance of 6–25 days for different grapevine varieties in Europe, with an average of 3–6 days response per 1 °C of warming during the last 30–50 years (Jones, 2007). In addition to a faster plant growth, the observed shortening in phase duration (Jones and Davis, 2000; Jones, 2007) may affect composition and quality of the wine. In fact, changes in sugar and acid quantities and composition, higher ethanol content and modification of the flavor, are some wine quality attributes that can be correlated to higher temperatures (de Orduña, 2010; Caffarra and Eccel, 2010; Bock et al., 2011; Caffarra and Eccel, 2011; Eccel et al., 2016). In the production of high-quality wines, variation of the chemical composition of grapes has been counteracted by applying new management strategies, *e.g.* improved farm practices or plant genotypes (Jones, 2007). Likewise, historical data show that grape growing areas in Europe have constantly changed following the thermal requirement needs. However, most projections imply a great and rapid climatic change, which can challenge our ability to adapt without an understanding of the impact (Jones, 2007). Currently, many European regions appear to be at or near their optimal growing-season temperatures (Jones et al., 2005a; Malheiro et al., 2010; Ruml et al., 2012), but grapevine cultivation area in Europe is expected to change further in the next century (Fraga et al., 2013), and notably in the Mediterranean region.

In terms of climate change, the Mediterranean region is a climate "hot spot", where temperature is expected to increase even more than in other world regions (Jones, 2007; Moriondo et al., 2013), leading to too warm conditions for the production of specific wine types (Jones et al., 2005a). For these reasons, wine industry is called to integrate adaptation strategies to deal with the impact of future climatic changes on phenology and quality, which are expected to be heterogeneous across varieties and regions (Jones et al., 2005a). A regional impact assessment is therefore crucial for more precise adaptation strategies in vineyards (Falcao et al., 2010; Fraga et al., 2012). In regions where grapevine cultivation is part of the agricultural, economic, and cultural heritage, changes in the wine production chain may heavily affect socioeconomic aspects, unless adaptation measures are taken (Bernetti et al., 2012). In the future, new grapevine-growing zones could be found closer to coasts in more northerly regions and at higher altitudes, where the temperature regime is currently too low for grapevine (Jones, 2007). Another adaptation option is to change varieties, choosing those more tolerant to high temperatures, although the success of a grape variety is not only linked to the attainment of its optimal thermal requirement during the growing season (Jones et al., 2005a).

In our case study, we took into consideration a geographically complex region, with a long history of wine production, the province of Trento in the Italian Alps. Wine industry is highly specialized in the region and several grapevine varieties are traditionally grown, both in the valley bottom and in several mountainous areas. The aim of this work was to assess the influence of climate change on grapevine phenology, considering the different features of five varieties and five phenological phases at different altitudes. We applied the phenological model FENOVITIS: a process-based model which is not restricted to local regions and showed good performance even in extremely warm years (Caffarra and Eccel, 2010). The FENOVITIS model describes plant development in terms of developmental units, calculated through relationships fitted on data obtained from experimentally measured studies. Chilling units are accumulated up to a critical chilling threshold simulating dormancy release ("Unified Model" for budburst in trees, proposed by Chuine, 2000), which is followed by heat accumulation (forcing units) up to a critical forcing threshold, simulating budburst. The inclusion of chilling and the use of an experimentally established relationship for quantifying the action of warm temperatures on growth makes the FENOVITIS model comparatively more process-based than the models based on bioclimatic indices (such as Winkler Index degree-days sum or others). The model was validated on datasets from four different sites from Northern Italy, yielding smaller prediction errors than the Winkler Index degree model, and a better performance during warm years, suggesting its reliability when applied to climate change scenarios (Caffarra and Eccel, 2010).

The computation chain was implemented into an open-source platform (ENVIRO) designed to harmonize climatic and agronomic spatial data as input to a system of scientific models. In particular, ENVIRO was developed as a web framework solution for scientific computing on distributed spatiotemporal datasets following the international standards established by the Open Geospatial Consortium. The platform is modular, with a typical WebGIS client server architecture, where the web interface enables mapping the vulnerability of agricultural systems to climate change. All spatial and thematic data are structured in a core database including different regional climate databases to assess the vulnerability of the viticulture system to climate change and the extent of effects in different micro-climates. The system can downscale the analysis to single vineyard resolution or upscale at specified aggregation zones, *e.g.* by considering different elevation belts. Notably, to support online geo-processing of large environmental models on climatic data, the ENVIRO platform can use graphical processing units and cluster/cloud computing.

2. Material and methods

2.1. Model calibration and validation

The FENOVITIS model was used to simulate the following growth stages (Lorenz et al., 1994): i) budburst (stage BBCH 09); ii) full flowering (stage BBCH 65), and iii) beginning of ripening or "veraison" (stage BBCH 81). The model, originally developed for Chardonnay, has been extended to other four grapevine varieties: Merlot, Pinot Noir, Pinot Gris and Sauvignon Blanc. Furthermore, the model was extended to take into account more phenological phases. We added the simulation of fruit set (stage BBCH 71) and berries ripe for harvest (stage BBCH 89) for all varieties based on a data set obtained with a monitoring survey that was running for two years (2009 and 2010). Data on the main BBCH stages were collected weekly or bi-weekly, in nine vineyards sited at different altitudes, in order to cover a wide climatic gradient (Caffarra et al., 2012). Heat units (HU) were calculated using the FENOVITIS model, as follows:

$$HU = \frac{1}{1 + e^{-0.26(Tm-16.06)}}$$

where Tm is the mean daily temperature.

The number of HU from chilling fulfillment to budburst (stage BBCH 09) and from budburst to flowering (stage BBCH 65), fruit set (stage

Table 1
The HU threshold for each variety per phenophase of the FENOVITS model.

Phenophase\Variety	Chardonnay	Merlot	Pinot Gris	Pinot Noir	Sauvignon Blanc
Budburst (BBCH 09)	27.16	23.01	20.10	27.93	20.76
Flowering (BBCH 65)	24.16	29.95	29.95	28.89	29.90
Fruit set (BBCH 71)	68.25	72.95	72.94	73.11	74.07
Veraison (BBCH 85)	81.27	86.95	86.95	85.01	86.73
Harvest (BBCH 89)	94.32	102.92	102.33	93.04	97.74

BBCH 71), veraison (stage BBCH 85) and harvest (stage BBCH 89) were subsequently calibrated for each variety (Table 1).

The model does not take into account thermal limitations due to high temperatures; this refinement has been proposed, *e.g.*, by Cola et al. (2014). However, the model validation proved not to underestimate the occurrence of late reproductive phases (Caffarra and Eccel, 2010).

2.2. Vineyard presence in Trentino

The morphology of the region is characterized by alpine landscape with valleys, ranging from 70 m (Lake Garda) to 3 769 m a.s.l. (Mt. Cevedale). The climate classification is mostly a *Cfb Kppen class* (temperate, middle latitudes climate, with no dry season). In more elevated, mountain areas the class shifts to *Dfc*, *i.e.* microthermal climate, humid all year round (Eccel et al., 2015).

The majority of world wine grape production is located at hilly elevations, mainly below 500 m (Gladstones, 2011). The province of Trento represents an exception with its traditional cultivation of grapevine in mountain areas. In fact, although vineyards mostly do not exceed altitudes of 850 m, some can be found at elevations as high as 1 200 m or even more.

Three varieties out of the five studied have vineyards located at altitudes above 300 m (Fig. 1 and Table 2). Pinot Noir is grown at the highest altitudes, at an average of 470 m (Inter-Quartile Range, IQR: 140 m), whereas the lowest vineyards mainly host Pinot Gris and Merlot, at an average of 195 m (IQR 64 m) and 198 m (IQR 96 m), respectively. The occurrence of high variations in altitude and the dispersed locations of vineyards among the same variety result in a high variation in the "calendar growing season" (CGS, from 21st March to 21st September) mean temperature in the province. The difference between the lowest (Pinot Noir) and the highest (Pinot Gris) CGS mean temperature is 1.62 °C for the baseline period.

2.3. Data set and temperature series modelling

The meteorological series used for processing and downscaling of temperature data were obtained from the regional database of Fondazione Edmund Mach (FEM) and from the Weather Service of the Autonomous Province of Trento (PAT). The temperature maps were computed by the Optimal Interpolation method (Uboldi et al., 2008), with a spatial resolution of 200 m. Interpolated daily temperature maps were available from the 1st of January 2001 to the 31st of December 2008 and validated using homogenized climate series for a subset of 33 weather stations. Validation was performed by computing the difference value for the daily average temperature between estimated and real values, at each of the 33 locations. The distribution of the first half of the stations (n = 16) range from −0.02 to 0. 75, and the distribution for the second half of the stations (n = 17) range from 0.78 – 1.83. Based on these results and on the statistical Wilcoxon test, both FEM and PAT datasets were considered, thus we extended our time series for the years 2009 to 2014 based on the same data analysis plan.

Climate projections for temperature and precipitation were created according to the protocol described in Eccel and Tomozeiu (2015). The procedure consists of several steps, in brief:

a) selection and pre-processing of instrumental series for the reference (past) period, 1961–1990;
b) setup of the statistical downscaling of the seasonal climate model using the Canonical Correlation Analysis (CCA) for ten selected series (details in the quoted reference and in Table 3);
c) application of the sub-downscaling algorithm to the remaining 33 series;
d) generation of daily series by applying a weather generation algorithm on the projected monthly values;
e) application of the phenological model to the daily series.

The method is detailed as follows, with reference to the list above. A total of 43 temperature series were selected for the area, gap-filled, and homogenized (according to Eccel et al., 2012) to form seasonally aggregated series. Only series with a minimum of 25 valid seasonal values (83% of series length) were taken into account to calculate climatic normals for the reference period 1961–1990; ten series were chosen, based on their climatic and geographical representativeness in the region and to their recording quality (series completeness, station history), to make up the input for statistical downscaling.

Climatic statistical downscaling was carried out with seasonal aggregation of data for four seasons (*e.g.* Winter: December to February). The statistical technique follows the PerfectProg approach, where suitable statistical relationships are found between a predictand and one or more observed variables that can be forecast by one or more numerical prediction models. In practice, the relationships are applied to the appropriate output of numerical prediction model to yield forecasts of the predictand. In essence, the output of the model is considered perfect, hence the name (definition from the internet "Meteorology Glossary" of American Meteorological Society). In our case, the links between large-scale (predictors) and local scale (predictands) are detected by CCA. Large-scale predictors are the atmospheric fields,

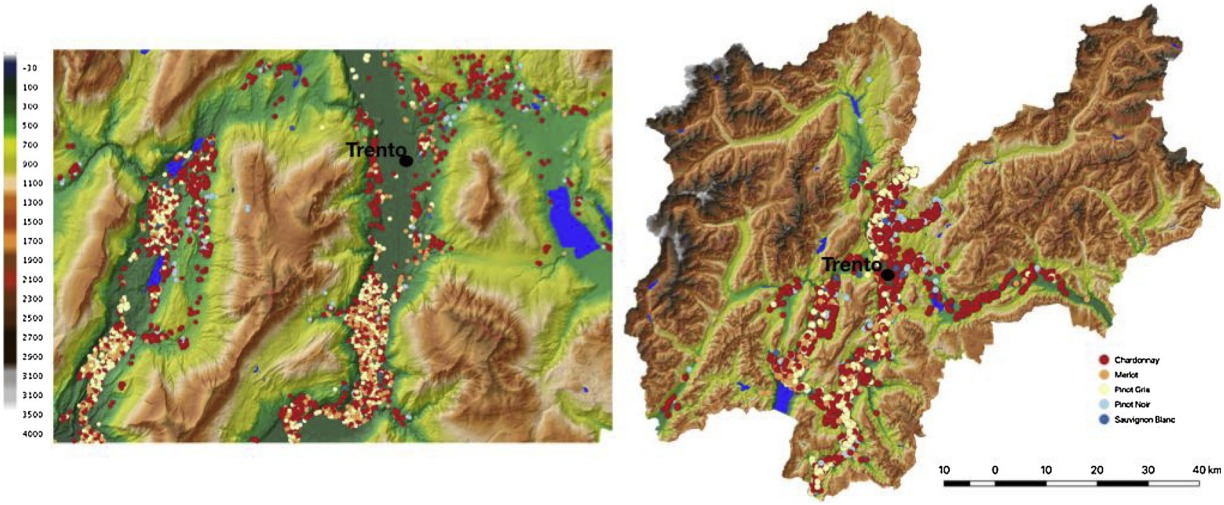

Fig. 1. Location of the vineyards in the study area (central section enlarged for details), with a total of 25 836 vineyards for five different varieties. For further information see Table 2.

Table 2
Total number of vineyards and the total area in hectares per single variety. Spatial mean temperature during the calendar growing season (21/3–21/9) for baseline period (2002–2014) (BP).

	Vineyards		Temperature BP	Altitude (m)				
Variety	Plots	Hectare	°C	Mean	Min	Q1	Q3	Max
Pinot Noir	1 208	4 394 384	16.87	470	74	410	550	950
Sauvignon Blanc	501	2 587 572	17.43	368	92	235	475	900
Chardonnay	12 270	53 104 669	17.60	339	71	203	467	775
Merlot	3 166	13 832 087	18.37	198	67	134	230	663
Pinot Gris	8 711	44 918 409	18.49	195	70	150	214	736

Table 3
List of the 10 stations used for the statistical downscaling (first step), with coordinates, altitude, and Köppen – Geiger climatic class.

Station name	Altitude (m)	Latitude (dg. N)	Longitude (dg. E)	Köppen – Geiger class
Pergine Valsugana	457	45°45'25"	10°59'59"	Cfb
Pieve Tesino	775	46°04'13"	11°37'11"	Cfb
Pejo	1 565	46°21'50"	10°40'32"	Cfb
Cles	685	46°21'43"	11°01'52"	Cfb
Mezzolombardo	225	46°12'51"	11°05'36"	Cfa
Pian Fedaia	2 040	46°27'32"	11°51'46"	Dfc
Trento Laste	312	46°04'18"	11°08'08"	Cfa
Folgaria	1 140	45°54'55"	11°09'52"	Cfb
Monte Bondone	1 552	46°01'19"	11°02'24"	Cfb
Cavalese	958	46°17'05"	11°27'06"	Cfb

considered at several atmospheric levels, each identified by its geopotential height. The best model performance was obtained with temperature at 850 hPa as predictor. The statistical downscaling scheme applied in this work was set up in the framework of the ENSEMBLES project (Van der Linden and Mitchell, 2009; Tomozeiu et al., 2013). The A1B scenario of IPCCs Special Report on Emission Scenarios (SRES) was used and the projections were constructed over the periods 2021–2050 and 2071–2099, as compared to 1961–1990 (Nakicenovic et al., 2000). Compared to the more recent "Representative Concentration Pathway (RCP) approach", in terms of GHG emissions, this scenario is close to RCP8.5 in the first-time window (2021–2050), while it is closer to RCP6.0 (an intermediate – high scenario) for the second time window 2071–2099. The choice of the predicted atmospheric scenarios is, to some extent, discretional; the socio-economic development pathway of RCP8.5, often used as a high-end business-as-usual scenario, is characterized by slow rates of economic development with limited convergence across regions; hence, it can be considered a truly pessimistic one (Riahi et al., 2011). The comparison of simulations carried out with different atmospheric scenarios is further discussed in Sections 3.1 and 3.2.

To widen the number of stations on which climatic projections are defined, a sub-downscaling algorithm was applied (Eccel and Tomozeiu, 2015), to downscale the seasonal climatic anomaly values, to the other 33 predicted weather stations (Fig. 2). It was carried out by a multivariate technique, Partial Least Squares Regression (PLSR), using R package "pls" (Mevik and Wehrens, 2007).

The phenological model used in this work needs daily temperature series as input. For this purpose, the weather generator RMAWGEN (Cordano and Eccel, 2016) was applied to the monthly mean values for the two future time windows (2021–2050 and 2071–2099). RMAWGEN was developed as an open source R package (R Development Core Team, 2008), published in the R-cran repository (http://cran.r-project.org/). It is an auto-regressive, multi-site stochastic generator, where both spatial and meteorological consistency are maintained in the simulated series over an area. This is important when seasonally-based comparisons have to be analyzed, as in the present work. To take into account the uncertainty of climatic projections, a high number of stochastic different daily realizations were generated. The result of the application of the weather generator was a number of simulations for each station and for each time window (200 annual realizations were used for each window, F1: 2021–2050, and F2: 2071–2099), each one characterized by random meteorological occurrences, while maintaining the general climatic features of each period as a whole. Weather series had a length of two solar years, necessary for the development of a complete phenological cycle. The coldest and the warmest realizations in the simulation sets, in the CGS, were chosen as the "cold" and the "warm" scenarios respectively, for the interpolation in F1 and F2. The choice to take the two extreme boundaries of our simulation allows for aleatory shifts in the meteorological events, reflecting the natural variability during growing season, at the same time maintaining climatological coherence in the realizations.

These series (two for each time window F1 and F2) were interpolated and used to map future distribution of vine phenology by applying the phenological model FENOVITIS. Temperature values were interpolated using Optimal Interpolation methods (Uboldi et al., 2008). The ENVIRO software was used to assess the effects of future climatic conditions on different grape varieties. The GeoServer ImageMosaic plugin was used to create mosaics from multiple georeferenced raster maps and study the time evolution of temperature. This operation was used in the ENVIRO database for assembling, indexing and optimizing the use of maps for analysis of climatic series.

3. Results and discussion

3.1. Climate change impact on grapevine phenophases

	Temperature (°C)			
Variety	F1C	F1W	F2C	F2W
Pinot Noir	17.79	18.31	19.12	19.99
Sauvignon Blanc	18.36	18.76	19.56	20.48
Chardonnay	18.46	18.87	19.67	20.6
Merlot	19.17	19.42	20.20	21.26
Pinot Gris	19.34	19.52	20.34	21.34

The response of the budburst phenophase to temperature increase varies significantly among the different grapevine varieties. The day of phenophase occurrence for each variety is computed as the average over the plots where the variety is grown. In this view, the average date is obtained over a geographical distribution. Compared to the baseline period, in the F1 time period (2021–2050), budburst dates are advanced for Pinot Noir (-7/-8 days) and Sauvignon Blanc (-5/-7 days), for cold/warm scenarios, respectively; further details are in Table 4. For Chardonnay and Merlot, the budburst dates are advanced of 2 days in the warm scenario and delayed in the cold scenario (Chardonnay: +1; Merlot: +5 days). For Pinot Gris budburst is delayed for both scenarios (cold: +8; warm: +2 days). In the F2 time period (2071–2099) Pinot Gris and Merlot have a delayed budburst compared to the baseline period (Pinot Gris cold: +1; Merlot cold: +4; Pinot Gris warm: +8;

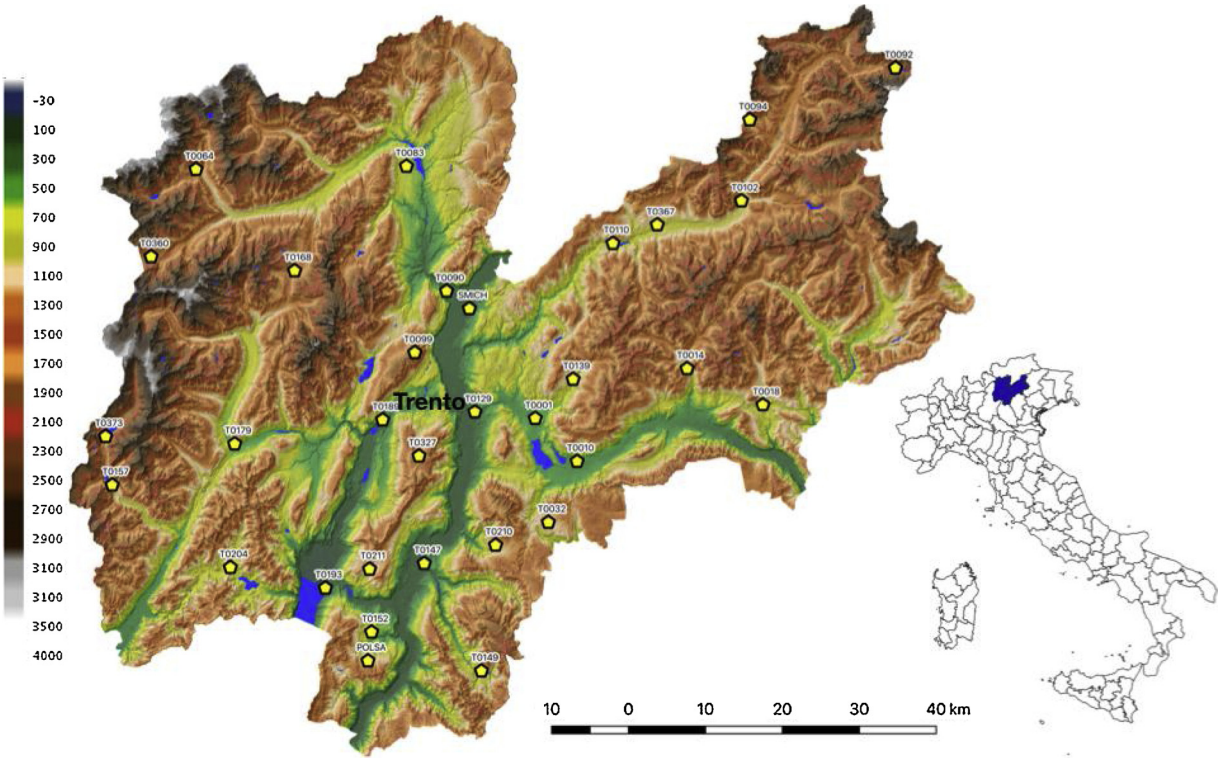

Fig. 2. Left: geographical location of the 33 weather stations in the study area (province of Trento, Italy - right panel).

Merlot warm: +5 days). For the remaining varieties (Pinot Noir, Chardonnay and Sauvignon Blanc) budburst is also advanced in comparison to the F1 period, with the highest difference of 18 days for Pinot Noir in the cold scenario. Notably, a warmer season can lead to a delayed budburst because this phenological mechanism is variety-specific, triggering endodormancy release by accumulation of chilling temperature.

The following three grapevine phenophases (flowering, fruit set, and veraison) show the same trend in response to temperature increase. The difference between the baseline period and the predicted scenarios increases for each following phase, hence the difference is smallest for flowering and highest for veraison. Pinot Noir has the largest advance shift in all time periods; for F1, flowering by 5 / 9 days, fruit set by 10 / 14 days, and veraison by 12 / 16 days (cold / warm scenario, respectively). The three phases are reached sooner ahead in the second time period. The Merlot variety is the least affected by the temperature change between the two time periods. The difference between the two extreme simulations, F1 cold and F2 warm, for Merlot, in comparison to the other four varieties (in parenthesis) is, flowering: 6 (10 - 14) days, fruit set: 7 (11 – 15) days, and veraison: 7 (11–15) days.

All varieties have an earlier harvest date. The two varieties grown at the lowest elevations, Pinot Gris and Merlot, have the smallest difference between baseline period and F1, from five to ten days. The highest differences are for the varieties Pinot Noir, Chardonnay and Sauvignon Blanc and range from 10 up to 18 days. In the second time period, harvest is also advanced, reaching 30 days in the warm scenario (Pinot Noir). For all varieties (except Merlot) the harvest is advanced for every sequential scenario as the temperature rises. For Merlot, harvest is advanced in F1 by 7 / 10 days, and in F2 by 8 / 15 days (cold / warm scenario, respectively). In the F2 cold scenario harvest is attained later than in F1 warm scenario.

The difference between the baseline period and the predicted scenarios increases significantly after budburst (Fig. 3), following the trend of increased temperatures in the different scenarios and determining a

Table 4
Occurrence of five different phenological stages (expressed in day of the year, spatial average per variety) during the periods 2021–2050 and 2071–2099 with two different scenarios per time period: cold (C) and warm (W). Difference in days between respective scenarios and the baseline period (c* and w*). Varieties ordered by increasing mean vineyard elevation.

Variety	Budburst				Flowering				Fruit set				Veraison				Harvest			
2021-2050	C	W	c*	w*	C	W	c*	w*	C	W	c*	w*	C	W	c*	w*	C	W	c*	w*
Pinot Noir	97	96	−7	−8	162	158	−5	−9	209	205	−10	−14	221	217	−12	−16	230	226	−14	−18
Sauvignon Blanc	100	98	−5	−7	162	158	−4	−8	208	205	−8	−11	220	217	−10	−13	233	230	−13	−16
Chardonnay	107	104	1	−2	156	153	−2	−5	202	199	−6	−9	215	213	−7	−10	230	227	−10	−13
Merlot	115	108	5	−2	164	161	−1	−4	208	205	−3	−6	222	219	−4	−7	240	236	−7	−10
Pinot Gris	107	101	8	2	160	158	1	−2	204	202	−2	−4	218	216	−3	−5	235	232	−5	−7
2071-2099																				
Pinot Noir	86	88	−18	−16	150	148	−17	−19	199	194	−20	−25	210	205	−22	−27	219	214	−25	−30
Sauvignon Blanc	89	93	−15	−12	151	148	−14	−17	199	194	−17	−22	211	206	−19	−24	223	218	−22	−28
Chardonnay	99	102	−7	−4	147	144	−11	−13	194	190	−14	−18	207	203	−15	−20	221	216	−18	−23
Merlot	119	115	8	5	164	158	−1	−7	207	202	−4	−10	221	215	−5	−11	239	232	−8	−15
Pinot Gris	100	103	1	4	152	150	−7	−9	198	193	−8	−13	212	207	−9	−14	228	223	−12	−17

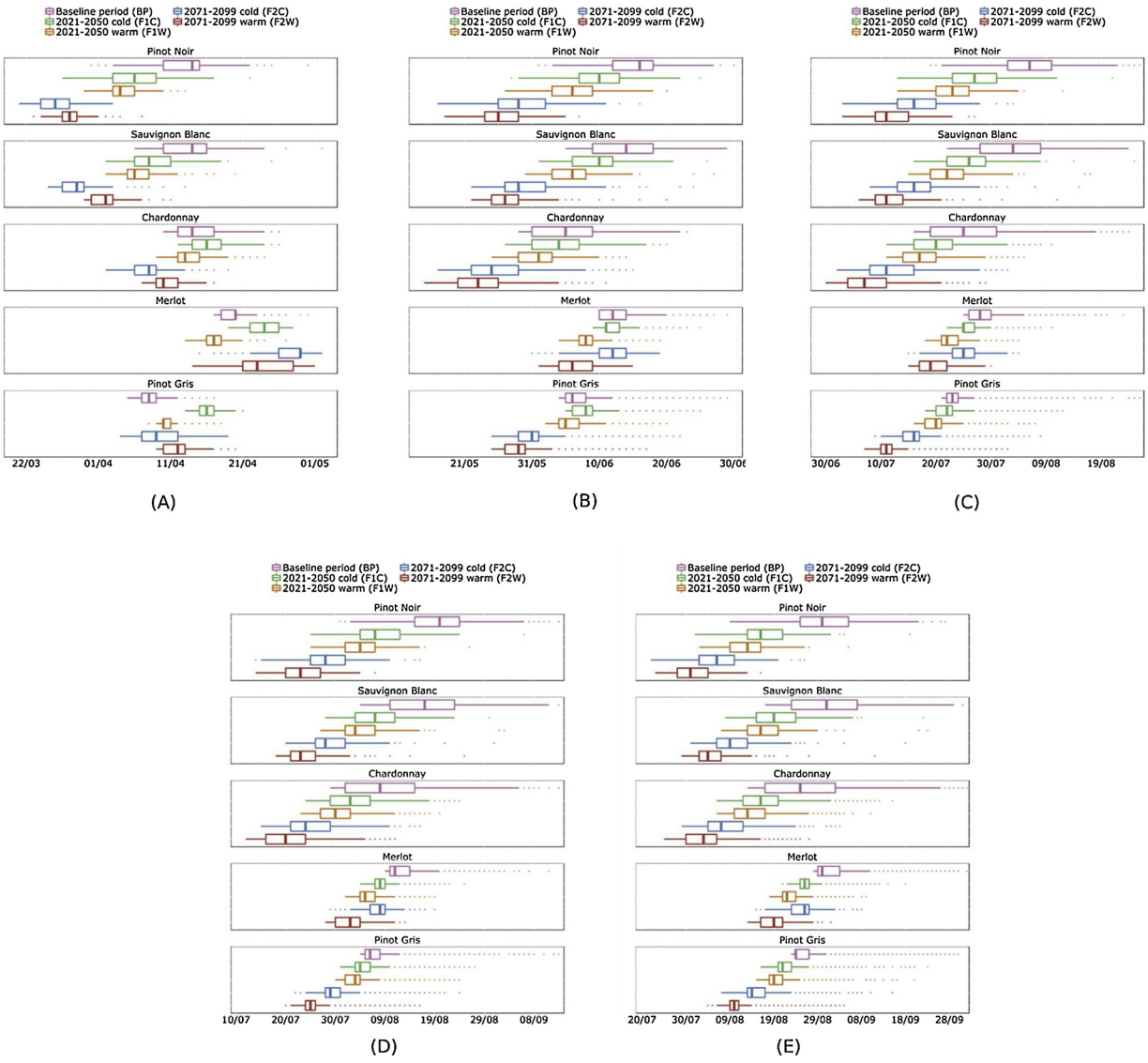

Fig. 3. Occurrence of five different phenological phases (ref.: Table 4) for five varieties. Box limits are first and third quartile.

Table 5
Length of the interval between phenological stages (expressed in days, spatial average per variety) during the periods 2021–2050 and 2071–2099 with two different scenarios per time period: cold (C) and warm (W). Difference in days between respective scenarios and the baseline period (c* and w*). Technical growing season goes from budburst to harvest.

Variety	Budburst-Flowering				Flowering - Veraison				Veraison - Harvest				Growing season			
2021-2050	C	W	c*	w*	C	W	c*	w*	C	W	c*	w*	C	W	c*	w*
Pinot Noir	65	62	2	−1	59	59	−7	−6	9	9	−2	−2	133	130	−7	−10
Sauvignon Blanc	62	61	0	−1	59	59	−6	−5	12	12	−3	−3	133	132	−8	−9
Chardonnay	48	49	−3	−3	60	60	−5	−5	15	14	−3	−3	123	123	−11	−11
Merlot	49	53	−5	−2	58	58	−3	−3	18	17	−2	−3	125	128	−11	−8
Pinot Gris	53	56	−7	−4	58	58	−4	−3	17	17	−2	−3	128	131	−13	−10
2071-2099																
Pinot Noir	64	60	1	−3	60	58	−6	−8	9	8	−2	−3	133	126	−7	−14
Sauvignon Blanc	62	56	1	−6	60	58	−5	−7	12	12	−3	−4	134	125	−7	−16
Chardonnay	48	43	−4	−9	61	58	−4	−6	14	14	−3	−4	123	115	−11	−19
Merlot	45	43	−11	−11	57	57	−4	−5	18	17	−3	−3	120	117	−16	−19
Pinot Gris	52	47	−8	−13	59	57	−2	−4	16	16	−3	−3	127	120	−13	−21

progressive advancement of the phases as they approach harvest. Budburst shows a diverse correlation with temperature scenarios due to chilling requirements. In fact, higher temperatures can lead to a delayed attainment of this phase. The highest advancement between baseline period and the future scenarios is found for the varieties grown at higher altitudes: Pinot Noir, Chardonnay and Sauvignon Blanc, and the lowest for Merlot and Pinot Gris.

There is a general scientific consensus on the advancement of

Table 6
Calculated coefficients of linear regression per 100 m for: temperature during the CGS (21/3–21/9), occurrence of phases budburst and harvest, and TGS duration, for the baseline period (2002–2014) (BP), the 2021–2050 cold scenario (F1C), the 2021–2050 warm scenario (F1W), the 2071–2099 cold scenario (F2C) and the 2071–2099 warm scenario (F2W).

Variety	BP	R^2	F1C	R^2	F1W	R^2	F2C	R^2	F2W	R^2
	Temperature									
Pinot Noir	−0.53	0.71	−0.53	0.67	−0.42	0.64	−0.41	0.48	−0.44	0.49
Sauvignon Blanc	−0.55	0.82	−0.55	0.8	−0.43	0.76	−0.42	0.67	−0.48	0.71
Chardonnay	−0.58	0.82	−0.53	0.76	−0.44	0.76	−0.44	0.67	−0.49	0.69
Merlot	−0.55	0.70	−0.50	0.63	−0.41	0.66	−0.44	0.65	−0.48	0.59
Pinot Gris	−0.60	0.74	−0.65	0.76	−0.48	0.68	−0.49	0.58	−0.56	0.70
	Budburst									
Pinot Noir	2.88	0.76	2.38	0.63	0.83	0.22	1.41	0.57	1.09	0.5
Sauvignon Blanc	2.51	0.87	2.08	0.77	0.54	0.14	1.24	0.55	0.33	0.06
Chardonnay	1.99	0.84	1.72	0.8	0.93	0.36	1.26	0.52	1.17	0.83
Merlot	0.99	0.23	−0.93	0.21	0.54	0.11	−1.1	0.16	−1.23	0.10
Pinot Gris	0.85	0.16	0.46	0.05	0.65	0.11	1.57	0.15	1.59	0.38
	Harvest									
Pinot Noir	6.28	0.67	3.6	0.59	2.78	0.52	2.8	0.4	2.35	0.42
Sauvignon Blanc	7.16	0.74	3.96	0.73	2.73	0.56	2.61	0.5	2.29	0.57
Chardonnay	6.27	0.75	3.4	0.72	2.48	0.61	2.92	0.6	2.89	0.71
Merlot	6.34	0.65	2.7	0.55	2.21	0.55	1.19	0.13	0.95	0.06
Pinot Gris	6.87	0.63	3.78	0.6	2.45	0.38	3.01	0.33	3.3	0.59
	TGS duration									
Pinot Noir	3.40	0.45	1.22	0.23	1.95	0.58	1.39	0.14	1.26	0.2
Sauvignon Blanc	4.64	0.61	1.88	0.46	2.19	0.69	1.36	0.21	1.96	0.48
Chardonnay	4.28	0.69	1.68	0.54	1.55	0.67	1.66	0.44	1.72	0.54
Merlot	5.34	0.74	3.63	0.76	1.68	0.68	2.29	0.58	2.18	0.70
Pinot Gris	6.02	0.71	3.32	0.65	1.8	0.46	1.44	0.19	1.71	0.35

grapevine phenology in the future, driven by global warming, even though quantitative results may differ according to the simulation features. For instance, de Cortázar-Atauri et al. (2017), for periods close to those considered in this work, found advance rates for three varieties in France quite similar to our results in the first simulation period (2030–2060). The choice of the atmospheric scenario (either RCP4.5 or RCP8.5) does not seem to yield particular differences in outcomes. This could be explained by the slight differences in the projected temperature series in the early decades of the simulation period, since only moderate differences exist among emission scenarios.

Results quantitatively similar to ours, with RCP4.5 and RCP8.5 scenarios, were obtained by Fraga et al. (2016) in Portugal by coupling global and regional climate models. These studies found that advancement rates for the period 2040–2070 (range: Budburst -4 / -1, Flowering -6 / -2, Veraison -15 / -5) were roughly similar to our results (range: Budburst -8 / +8, Flowering -9 / +1, Veraison -16 / -3) for the first simulation period (F1: 2021–2050). Similarly, for north-east Spain, modelling of grapevine phenology gave an estimated advance of phenology aligned with these studies, as well as with ours (Ramos, 2017). Differently from these studies, we found lower anticipation rates in the early phases (*e.g.* compared to the results of de Cortázar-Atauri et al., 2017). This result may lead to proneness to frost episodes; even if nowadays there is not a frequent occurrence in south-alpine mountain viticulture, due to the longer times of spring phenophases of the cultivars grown in these areas, it is often claimed that phenology advance may expose vineyards to higher frost risks. The minor advance in budburst and flowering seems to weaken this prospect in our case; however a dedicated analysis should be carried out to take into account differences in minimum and maximum temperature evolution.

Overall, all quoted studies and ours report important differences among varieties in the simulated scenarios. We deem that this can be taken as a warning about an overconfident interpretation of model results, given the different responses each variety has to the thermal driver (Fila et al., 2014).

3.2. Climate change impact on phenophase duration

Phenophase duration (interval between phases) and growing season length affect the time available to plants to photosynthesize sugars, which may adversely impact the quality of grapes. The varieties with the largest IQR in altitude, thus the highest temperature spread among vineyards, have, consequently, the longest phase duration (Fig. 3). Moreover, single phases are shorter in future scenarios compared to baseline period. The phase duration is longest for flowering, fruit set and veraison for all varieties. The Pinot Noir and Sauvignon Blanc intervals are less affected by the temperature increase in comparison to the baseline period as they differ in the F1 period by +2 / -1 days and by 0 /-1 day and in the F2 period by +1 / -3 days and +1 / -6 days (cold / warm scenario, respectively).

The flowering-to-veraison interval (phases: flowering, fruit set and veraison) directly depends on temperature and highlights the different response to it among varieties (Gladstones, 2011). In F1 this interval is shortened by between 3 days (Merlot) and 7 days (Pinot Noir). Duration change ranges in the limited time span of +1 to -2 days among the four scenarios (F1 and F2, warm and cold). As seen in the previous section, the highest difference between baseline period and future scenarios is found for Pinot Noir, Sauvignon Blanc and Chardonnay and the lowest for Merlot and Pinot Gris.

The veraison-to-harvest interval is least reduced in the future scenarios, ranging from -2 to -3 days in the F1 period and from -2 to -4 days. This change is also very similar among varieties, with just one day of difference for each scenario. From veraison until harvest the plant accumulates important sugar and acid amounts, consolidating flavor and quality attributes (Jones, 2007); hence, if this time is either too short or too long, quality may be affected.

The “technical growing season” (TGS: budburst to harvest) duration ranges from 133 days (Merlot) to 141 days (Sauvignon Blanc) during the baseline period (Table 5). In F1 the season is reduced by 8 / 13 days, considering both warm and cold scenarios. For all varieties, with the exception of Merlot, the duration in the three scenarios F1 cold, F1 warm, and F2 cold, only differs by ± 3 days. On the contrary, in the F2 warm scenario it is decreased by 7–9 days, lasting from 115 up to 126 days. Thus, an increase in the TGS temperature in the range of 0.85 °C–1.97 °C (2021–2050 cold and 2071–2099 cold scenarios, respectively) (Tables 2 and 4) is not going to substantially change its length. With a further temperature increase of 0.97 °C (+2.94 °C

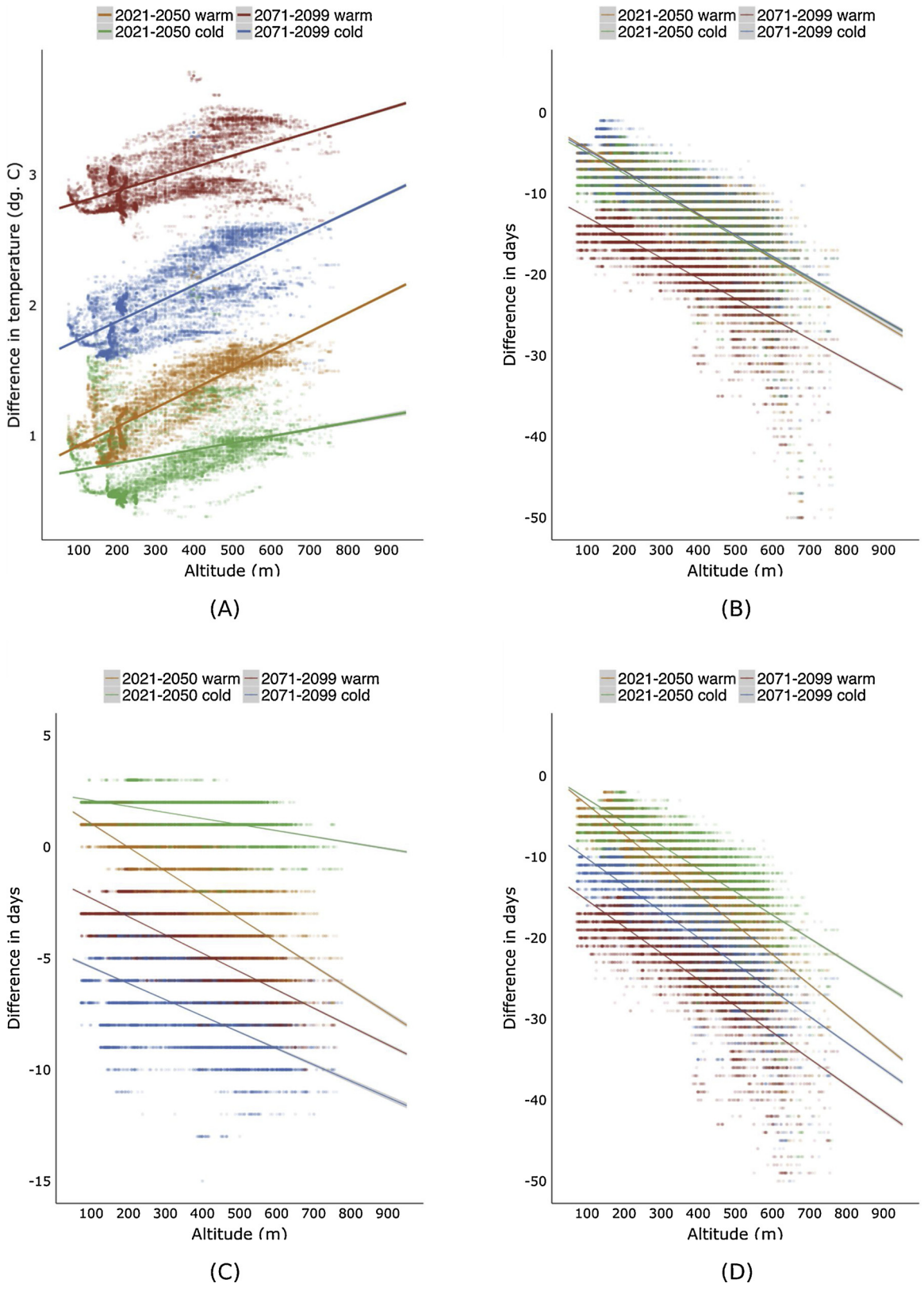

Fig. 4. Linear regression of the difference between baseline period and future scenarios *vs.* altitude for the variety Chardonnay: A) CGS temperature B) TGS duration C) Budburst date change D) Harvest date change.

compared to baseline period, 2071–2099 warm scenario) (Tables 2 and 4) the duration is reduced significantly for four varieties: Pinot Gris, Pinot Noir, Chardonnay and Sauvignon Blanc. The TGS length for Merlot has a different response to temperature. In F1 it is shorter by 11 days and 8 days, cold and warm scenarios, respectively, lasting 125 to 128 days. In F2 it is further reduced by 5 and 11 days, cold and warm scenarios, respectively, lasting 120 - 117 days. Note that even if varieties Pinot Gris and Merlot had the shortest advancement of phases in

future scenarios and the shortest reduction in flowering-to-veraison interval, budburst delay for both varieties leads to the highest decrease of the TGS length. The other three varieties display an advanced budburst; this shifts the TGS back in time to some extent, while still leading to an overall significantly shorter duration. There is also a general consensus on the prediction of a shortening of the phenological season from early (spring) to late (summer - autumn) stages, as an obvious consequence of the stronger advancement of summer phases, compared to the spring ones (Ramos, 2017; de Cortázar-Atauri et al., 2017; Fraga et al., 2016; Fila et al., 2014).

3.3. Influence of altitude on grapevine phenology

The altitude of vineyards for the five varieties ranges from 67 m to 950 m above sea level (Table 2). Mean growing season temperature, budburst (the earliest phase), harvest (the latest phase), and the length of TGS (budburst to harvest interval) were assessed for their statistical relationship with altitude for the baseline period and the future scenarios. The correlation between the timing of the different phenophases and altitude is statistically significant for all scenarios with a p-value < 0.001. The mean TGS temperature in the baseline period decreases by 0.53–0.60 °C $(100\,m)^{-1}$ for the different varieties, see Table 6.

In the future scenarios, the temperature elevational gradient decreases, with the exception of Pinot Gris vineyards (F1 cold scenario), where it increases (in absolute values) from -0.60 to -0.65 °C $(100\,m)^{-1}$. The mean temperature for the different varieties shows the lowest negative altitudinal rate in the F1 warm scenario (0.41–0.48 °C $(100\,m)^{-1}$) and F2 cold scenario (0.41–0.49 °C $(100\,m)^{-1}$), with the highest temperature gradient in the baseline period.

The temperature is projected to increase more at higher altitudes, thus decreasing altitudinal gradient. As a consequence, the time span between different phenological phases at different altitudes is expected to shorten. In practice, a comparatively shorter TGS is predicted for vineyards located at higher altitudes. Between the scenarios F1 cold, F1 warm, and F2 cold this difference is marginal for all varieties, with the exception of Merlot (Fig. 4). On the contrary, for F2 warm it increases significantly. The altitudinal gradient of timing for budburst ranges from 0.85 to 2.88 days $(100\,m)^{-1}$ for the baseline period. It shows a decreasing trend in future scenarios for all varieties except Pinot Gris. The latter increases in F2, from 0.85 days $(100\,m)^{-1}$ in the baseline period to 1.57 and 1.59 days $(100\,m)^{-1}$ (cold and warm scenarios, respectively). The lowest difference is for scenario F1 warm ($R2 < 0.36$), which also has the lowest temperature gradient.

The harvest time is significantly more influenced by altitude than the earliest phenological phase (budburst). In the baseline period the difference between varieties ranges from 6.27 to 7.16 days $(100\,m)^{-1}$. The highest difference in altitudinal rates for phenology can be found from baseline period to F1 cold period, in the range 2.70–3.96 days $(100\,m)^{-1}$. As for temperature, the lowest differences are found for the F1 warm and F2 cold scenarios. With the exception of Merlot, which decreases significantly for every sequential phase. The correlation of phenology with height varies between different scenarios, depending on the different projected seasons, which have different temperature fluctuations, and specific variety sensitivity to these variations. Even so, it is observed that in the period 2021–2099 harvest timing is expected to decrease by approximately 3 days $(100\,m)^{-1}$, leading to a more concentrated harvest window for growers and especially for wineries, which are supposed to separately deal with each variety.

4. Conclusion

The expected effects of climate change are not homogeneous in a mountainous province like Trentino. In this region, a significant higher change in grapevine phenology is expected, following the higher increase in phenological forcing temperature at higher altitudes, where base values are lower. Consequences on grapevine phenology are already expected in the next 30 years and until the end of this century. Harvest will occur earlier than current conditions: by one to two weeks in the years 2021–2050 and up to four weeks in the years 2071–2099. A shorter period between budburst and harvest (TGS) is expected from simulations, due to phenological advancement. Harvest time advance will likely bring a shortening of the harvest time gap between mountain and valley-bottom sites, due to the faster phenological development at higher elevations. Hence, this change will require management adjustments in work scheduling for both grapevine growers and wine producers.

The varieties considered in this study had an uneven number of vineyards, with a scattered geo-localization pattern, resulting in an irregular influence of temperature change in their growing sites. For this reason, we could not compare sensitivity to temperature change among varieties, but differences among varieties were assessed based on their locations. Pinot Gris and Merlot, grown in vineyards located at the lowest altitudes, show the lowest advancement of phases but the highest shortening of the growing season. Pinot Noir, Sauvignon Blanc and Chardonnay, which are located at higher altitudes, had an opposite behavior.

Two possible adaptation strategies are envisaged in the area: replace existing varieties with varieties more suited to warmer climates, and/or growing the existing varieties in cooler areas, namely moving to higher altitudes. A proactive approach of grapevine growers to find new suitable areas for traditional varieties would bring benefits to quality maintenance of some wines and, at the same time, the introduction of new varieties could open a new market. In such case, a further assessment of the effects of the local environmental conditions on wine quality as well as a market assessment for new grape varieties is recommended. As a future perspective, we recommend development of a methodology for high-resolution crop suitability analysis that takes into consideration historical and predicted growing patterns from this study as well as the correlated quality parameters per variety. By working with a high-resolution approach, the geographical locations could be characterized both as plot-based and variety-specific, allowing the development of a more precise long-term adaptation approach. Furthermore, the model could be used to evaluate the impact of extreme weather events (*e.g.* heat waves), which have increased in the past decades as a consequence of climate change. Such exposures are expected to have an additional impact on phenology of crops and the final quality of wine. We thus wish for an inclusion of the assessment of short-term temperature extremes in future suitability and climate change adaptation.

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